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Stable Vortices Within Vein Cuffs Inhibit Anastomotic Myointimal Hyperplasia?

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Objectives: *Interposition vein cuffs improve the patency of below-knee ePTFE arterial grafts, and there is evidence that they do so, at least in part, by modifying the distribution of myointimal hyperplasia (MIH) at the distal anastomosis. Alteration of local haemodynamics is one of the mechanisms which might be involved. The purpose of this study was to characterise the local haemodynamics within an interposition vein cuff.*

Material and Methods: *Flow patterns have been analysed in a laboratory model of cuffed anastomosis and compared with observations made in patients by cine intra-arterial digital subtraction angiography (IA DSA) and dynamic colour duplex scanning.*

Results: *In contrast to non-cuffed anastomoses in which the flow is predominately laminar, cuffed anastomoses are associated with the formation of a coherent vortex.*

Conclusion: *High frictional forces or shear stress exerted upon the arterial wall by the vortex could explain the beneficial effect of a cuff upon anastomotic MIH, in which case the optimal configuration of small vessel anastomoses would be that which most effectively promotes the formation of this type of vortex.*

Key Words: MIH; Miller cuff; Interposition cuff; Vortex; Vascular anastomosis; Colour Doppler; Cine intra-arterial digital subtraction angiography; Laboratory model.

Introduction

Limb salvage or the relief of symptoms in lower extremity arterial disease is best accomplished by restoration of flow to an appropriate patent distal artery.[1] Autogenous saphenous vein (ASV) has been accepted as the most suitable graft material for such arterial reconstruction below the inguinal ligament.[2] The fact that not all patients have a vein of adequate length and calibre, coupled with the increased demand for venous graft material brought about by coronary artery bypass surgery, has led to increasing demands for new synthetic materials such as PTFE. However, the initial optimistic results associated with the use of PTFE were later tempered by disappointing long-term graft patency figures.[3,4] Graft failure a month or more after insertion is commonly due to myoinimital hyperplasia (MIH) or progression of distal disease. MIH localises preferentially at the outlet of the graft at the graft-to-artery anastomosis and on the floor of the recipient artery, just beyond the anastomosis, as described by Sottiurai.[5] The factors thought to be responsible for the formation of MIH include: an initial injury to the endothelium; abnormal shear stress upon the arterial wall; interaction between components of the flow surface; and elements of circulating blood and compliance mismatch.[6]

There is evidence that the early failure rate of prosthetic bypass grafts anastomosed to infrageniculate arteries is reduced by the addition of a cuff of autologous vein interposed between the graft and the recipient artery at the distal anastomosis.[7–9] This beneficial effect appears to be associated with a reduced tendency for MIH to accumulate in the recipient artery, as it has been observed that when a cuffed graft does fail patency of the run-off vessel is usually preserved.[9] It is often possible to demonstrate MIH within the vein cuff itself, particularly in the zone immediately adjacent to the graft. On present evidence it is not yet possible to say whether this apparent redistribution of MIH from recipient artery to the more accommodating vein cuff is capable of preventing or merely delaying

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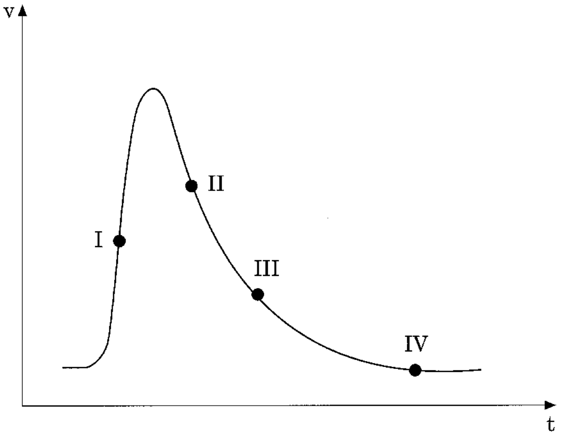

Fig. 1. Maximum frequency envelope waveform derived from spectral Doppler, also showing the intervals in the cycle at which images were captured.

graft failure. But an understanding of the mechanisms by which the presence of a cuff protects the recipient artery from MIH may lead to improvements in technique or cuff design with further beneficial impact on graft patency. Working on the hypothesis that altered local haemodynamics are likely to be important,[10,11] we have investigated the flow patterns at the distal anastomoses in patients with cuffed femorodistal PTFE grafts. Two techniques have been employed: dynamic colour duplex scanning and cine intra-arterial digital subtraction angiography. To assist interpretation of the images obtained by these two techniques, *in vitro* flow visualisation experiments were undertaken on replicas of cuffed vascular anastomoses.

Methods

Ultrasound

A colour flow scanner (Diasonics Spectra) provided with a 10 MHz linear array probe was used to insonate the anastomoses. The data were recorded onto a S-VHS video tape for later analysis. Colour flow and B-mode images were obtained in planes parallel, and at right angles, to the recipient artery. The anastomoses, including segments of the graft and the recipient artery, were imaged to provide a dynamic picture of the local haemodynamics at the anastomosis region. Spectral Doppler data from selected regions were recorded. The colour map was selected to depict flow towards the ultrasound beam in red and flow away from the beam as blue. Turbulent flow is shown in green and yellow. When the Doppler shift exceeds a certain threshold (Nyquist limit), the flow direction is incorrectly indicated. This was avoided by using a high pulse repetition frequency.

Cine intra-arterial digital subtraction angiography (IA DSA)

Visualisation of the interposition vein cuff using IA DSA was obtained by positioning a fine delivery catheter, introduced via the femoral artery, within the graft just proximal to the interposition vein cuff. Low osmolar non-ionic contrast material was injected at a rate between 1 and 10 ml/s for periods ranging from 0.5 to 2 s to produce a thin trace or streak line. Images were acquired at a rate of 25 frames/s and recorded onto a S-VHS tape for subsequent haemodynamic analysis.

Experimental model

A Miller cuff anastomosis was constructed from 3.5 mm internal diameter PTFE grafts (to represent the recipient artery) and 6 mm externally supported expanded PTFE grafts and human saphenous vein. An internal cast of the anastomosis was produced using a quick-setting acrylic resin. A hollow cast of this anastomosis was then produced by the lost wax technique[12] using a clear polyurethane solution (Tecoflex, SG 93a Themedics Inc. MA, U.S.A.).

The circulating fluid was a 40% w/w aqueous glycerol solution containing tracer particles with sizes ranging from 75 to 150 mm to a concentration of 0.2% w/w. Pulsatile flow was generated by means of a purpose-built, computer-controlled piston pump[13] programmed to deliver a similar waveform to that obtained from the mid-graft regions in patients with Miller cuff anastomoses (Fig. 1). The mean flow rate was 180 ml/min, which corresponds to a Reynolds number of 167 ($Re = rDV/m$, where r is the density, D the diameter of the graft, V is the mean velocity and m the dynamic viscosity of the fluid), the frequency of the waveform was 1.25 Hz and the Womersley α parameter was 4.8 ($\alpha = D/2V(2\pi f/m)$, where f is the frequency of the pulsatile flow). Flow structures were visualised by illuminating the tracer particles suspended in the model fluid using a thin sheet of helium-laser light in different planes parallel and normal to the plane of symmetry of the anastomosis. The flow patterns were recorded using a video camera operated at 25 frames/s and stored on S-VHS tape for

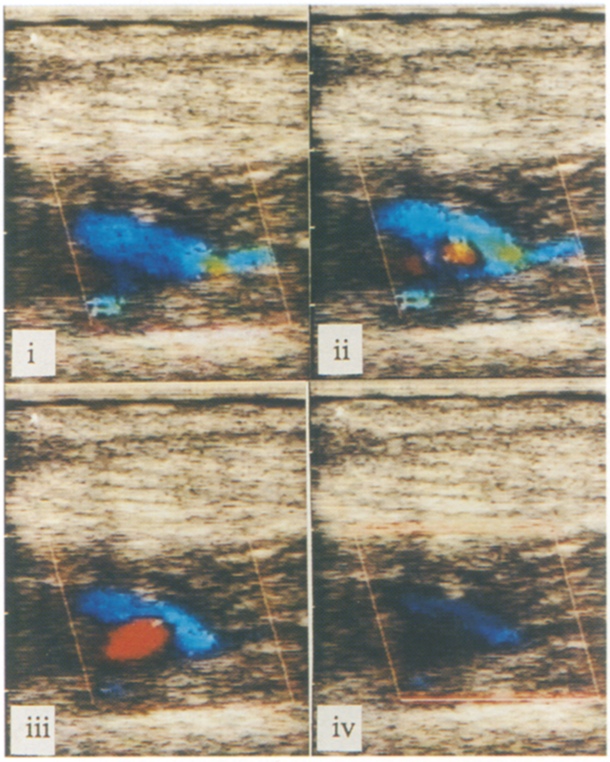

Fig. 2. Snapshots of the colour Doppler images of the Miller cuff anastomosis, captured at four intervals during the cardiac cycle (frames i–iv).

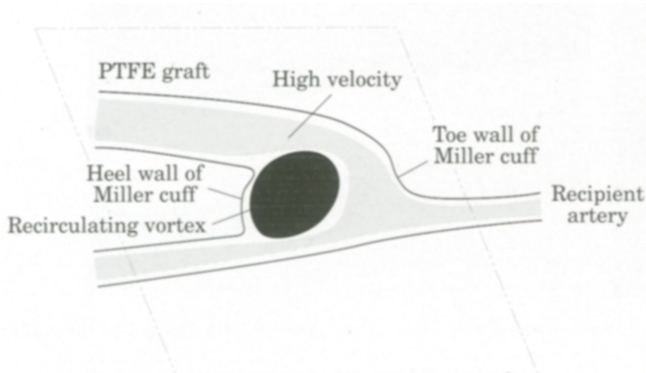

Fig. 3. Outline of the principal components of the colour Doppler images.

subsequent analysis. The flow patterns were observed under pulsatile flow conditions similar to those observed in patients with Miller cuff anastomoses.

Results

Ultrasound

The colour display of a Miller cuff anastomosis, captured at four intervals during the cardiac cycle, is shown in Fig. 2. The maximum frequency envelope waveform derived from the spectral Doppler data is shown in Fig. 1. The times during the cardiac cycle when each colour Doppler frame was obtained are indicated on this waveform. The principal components of the colour Doppler images are outlined in diagrammatical form in Fig. 3. The flow pattern at the mid-acceleration phase (frame i, Fig. 2) is characterised by the blue colour in the graft and recipient artery, indicating that the flow followed the contour of the walls. The absence of any colour at the heel of the cuff suggested that the velocities in this region were low. Just after peak flow (frame ii), a small red region formed in the centre of the cuff and occupied an increasingly larger area of the cuff as deceleration progressed (frame iii). In late diastole the anastomosis was partially filled with dark blue colour, indicating that the velocities were below the velocity range setting of the instrument.

Cine intra-arterial digital subtraction angiography

The progression of the contrast medium, and its distribution in the proximal and distal outflows of the artery as it is injected at a rate of 1 ml/s is shown in Fig. 4a and b. On the lateral view the streak line produced by the contrast medium performed a regular swirling motion as it entered the cuff (Fig. 4a). At peak flow this phenomenon occupied most of the cuff volume. Later in the cardiac cycle, as the streak line moved from the heel to the toe, part of the streak line appeared to break off and became trapped in a recirculation region at the heel (Fig. 5). On the AP view (Fig. 4b), the contrast medium was seen to enter the cuff centrally early in the cardiac cycle. Approximately one-third of the way into the cuff, the streak line began to separate into two symmetrical swirls. Further along the cuff, an additional pair of swirls was formed.

Experimental model

The flow visualisation experiments showed that the flow patterns are highly three-dimensional. Fig. 6 shows the flow patterns recorded in the lateral view at four different times in the flow cycle. The flow through the proximal and distal outflow vessels was equal. During mid-acceleration phase (frame i), the

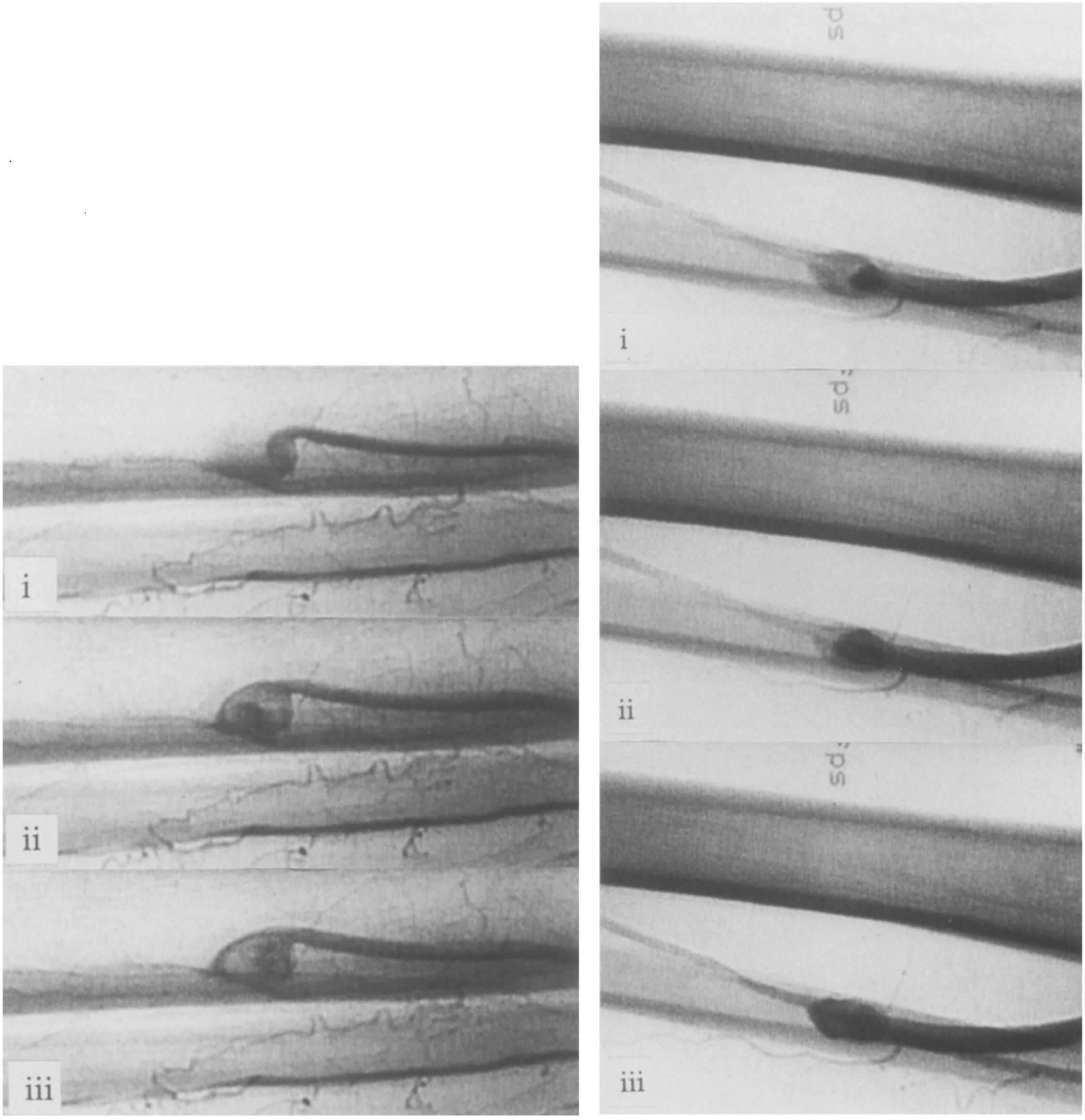

Fig. 4. (a) Lateral view of the cine IA DSA images of the Miller cuff; (b) antero-posterior view of the cine IA DSA images of the Miller cuff.

flow through the anastomosis was laminar with little boundary layer separation. A stagnation point was formed on the floor of the artery where the flow divides into the proximal and distal outflow vessels. This flow pattern changed very little during the rest of the acceleration phase. After peak velocity the boundary layer separated at the graft heel, producing a three-dimensional vortex (anticlockwise fluid rotation) in the central part of the cuff (frame ii). As deceleration progressed, the size and velocity within the vortex increased (frame iii). The vortex appeared to be coherent and there is no evidence of the random particle motions that would have suggested turbulent flow. The vortex shifted the fluid entering the cuff towards the cuff toe and effectively reduced the cross-sectional area for the flow through the cuff. This also had the effect of displacing the stagnation point distally, where it remained for the rest of the cycle. The vortex remained in the cuff during the rest of the cycle, although the flow dropped to approximately one-third of its peak value (frame iv). As the next cycle arrived, the vortex was completely removed and the flow pattern reverted back to a laminar regime (frame i). Flow in the vortex was unidirectional and thus in contrast to normal laminar flow, in which flow reversal occurs under resting conditions.

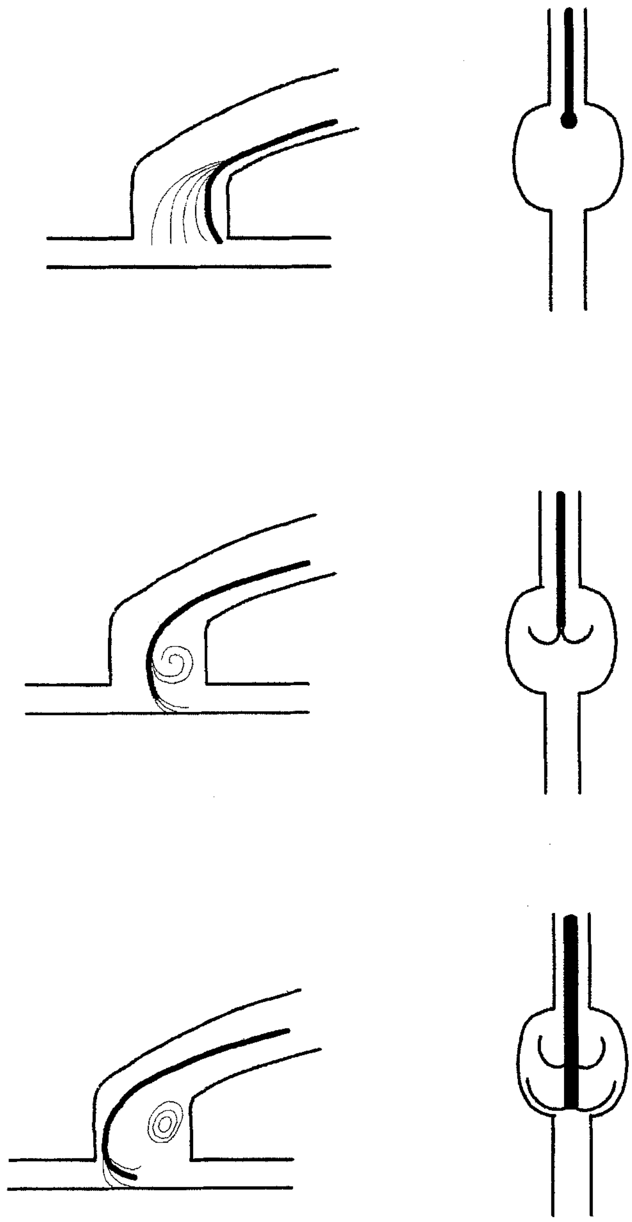

Fig. 5. Diagram of the principal components of the cine IA DSA.

Discussion

Augmentation of arterial blood flow to an ischaemic extremity is the basis of all reconstructive vascular surgery. Autologous saphenous vein is still the conduit of choice over other prosthetic materials such as PTFE.[14] The poor patency rates of PTFE have been attributed to the development of MIH at the distal anastomosis,[15] but there is increasing evidence that the interposition of a vein cuff[8,9,16] or a vein patch[17] does improve graft patency rates. A prospective study[18] has strengthened the case for the routine use of interposition vein cuff for infrageniculate arterial bypass. In controlled animal experiments, the use of a vein patch has been shown to minimise the accretion of MIH.[19,20] What remains unclear now is the exact mechanism by which interposition vein cuffs have a beneficial effect on the formation of MIH at the distal anastomosis. The origin of MIH seems to be multifactorial, including haemodynamic factors,[21] graft artery compliance mismatch[22] and chronic endothelial injury.[23] The impact of interposition vein cuffs on any of these factors has so far been uncertain.

The results of this study show that flow in a Miller cuff is associated with a highly specific flow pattern. This consists of a large unidirectional coherent vortex which is present during most of the cardiac cycle. Colour Doppler and cine IA DSA images obtained from patients shown that these observations are highly relevant to clinical practice, because the presence of a similar flow pattern was confirmed in all Miller cuff anastomoses examined.

Flow in the observed vortices is unidirectional and at a relatively high velocity, and therefore the mean shear stress exerted by it upon the arterial wall is greater than the associated with normal laminar flow. It is generally accepted that low wall mean shear stress is associated with the development of MIH[24–26] and, conversely, that high mean wall shear stress inhibits MIH. Thus the high shear stress effected by the vortex on the wall could explain, at least in part, the beneficial effect of the cuff on anastomotic MIH. An added factor may be that the vortex prevents blood elements, especially platelets, from coming into contact with the arterial wall and preventing their activation. Thus the vortices which are generated within the Miller cuff anastomosis could be responsible, wholly or partially, for the improved performance of PTFE grafts with interposition vein cuffs.

Practical applications are two-fold. Firstly, analysis of dynamic images obtained by the techniques described here may indicate how the shape of vein cuffs could be modified further in order to optimise flow characteristics and reduce the stimulus for MIH to occur at these anastomoses. Secondly, if the basic hypothesis is correct, it follows that it is the geometry of the anastomosis which is important in suppressing MIH, and not the inclusion of autologous venous material. Therefore, one could speculate that reproduction of the ideal geometry produced by shaping an end of a PTFE graft[27] could be as effective as an interposition vein cuff, and this would simplify the surgical procedure considerably.

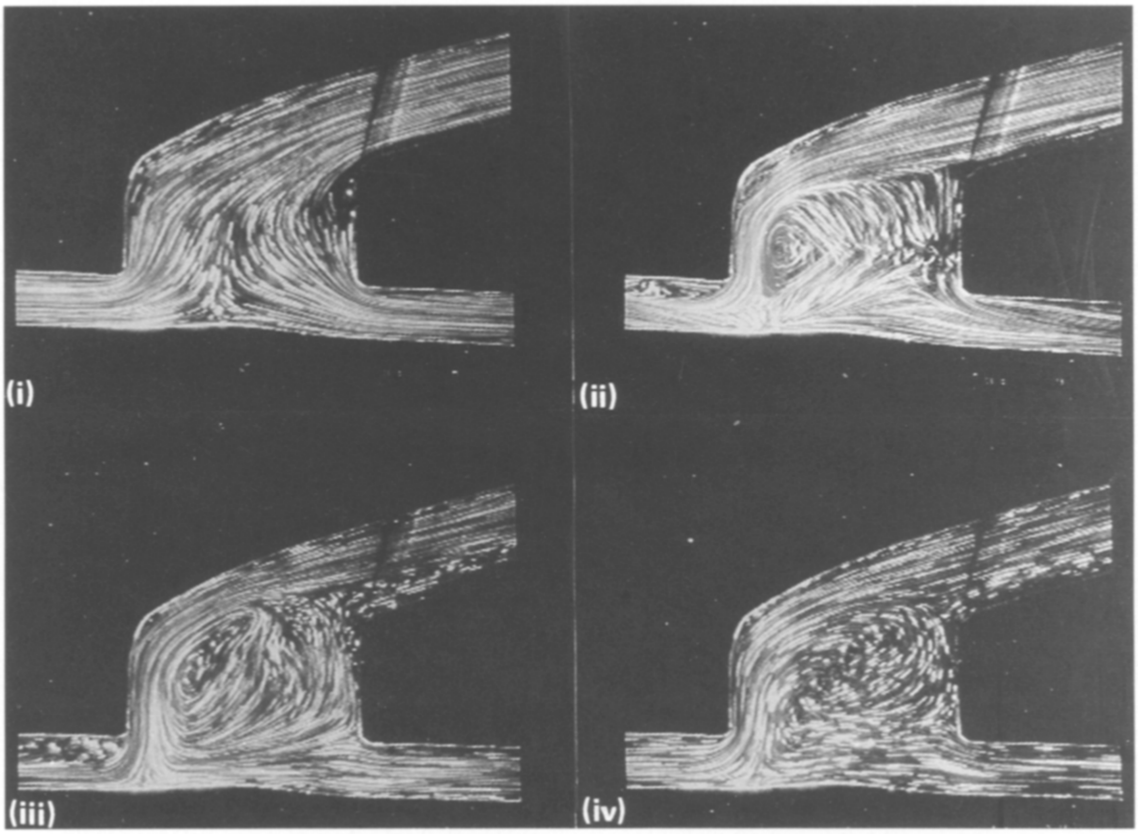

Fig. 6. Photographs of the flow patterns obtained in the flow visualisation model (frames i–iv).

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